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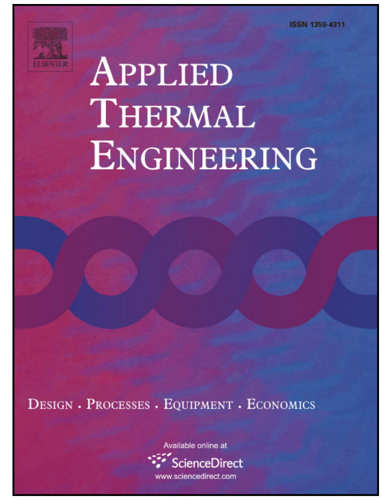

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Demand side management analysis of a supermarket integrated HVAC, refrigeration and water loop heat pump system

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Abstract

Supermarkets are intensive energy consumers because of a high electricity demand, mainly due to refrigeration utilities. Thus, in this work a supermarket integrated HVAC, refrigeration and water loop heat pump (WLHP) system was analyzed according to a demand side management approach, adopting a demand response strategy coupled with real-time pricing predictive rule based controls. The system was modeled with TRNSYS and several DR strategies were applied to both the space heating/cooling and the WLHP to determine the plant configuration with the most effective electricity cost saving. It was found that two setups guarantee the highest economic savings. The first consists of a predictive rule based control applied to the space heating/cooling only, which is basically inexpensive and allows an annual cost saving of 4.06% respect to the baseline configuration. The second, instead, combines predictive rule based controls applied to both the space heating/cooling and the WLHP auxiliary heater, and shows the best performance with the adoption of a 200 m^3 water-based thermal energy storage. Respect to the baseline, this configuration provides an annual

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cost saving of 4.67%.

Keywords: Real-time pricing; Predictive rule based control; Thermal energy storage; Flexibility; Day-ahead market

1. Introduction

The European Renewable Energy Directive sets a target of at least 20% of electricity produced from renewable sources by 2020 [1]. To date, one of the key challenges to overcome the low predictability of renewable energies lies in the increase of flexibility of energy networks. With a larger flexibility, energy systems could improve their reliability and make the energy price more competitive.

A way to improve the flexibility of an energy system lies in the adoption of demand side management [2]. DSM includes a set of polices able to influence the customer's energy demand, changing the shape of the load and helping to optimize the overall power system from generation to end use [3]. An important DSM policy is referred to as demand response (DR) and consists of changes in electricity use by end customers in response to variations of the electricity price over time [4].

Given the more and more relevant energy consumption of the refrigeration sector (17% of the overall electricity used worldwide [5, 6]), nowadays there is a growing interest towards the adoption of DSM strategies by refrigeration technologies. In literature, several works tried to apply DSM strategies to refrigeration applications. Referring to domestic refrigerators, Stadler et al. [7] compared two types of control signals to use the thermal storage of a high number of controllable refrigerators as balancing power. The authors showed that the two control signals can be used for short term reserves with delivery within 15 minutes, but they differ in possible shapes of the resulting load curves and in the reaction time of the controlled system. In 2013, Niro et al. [8] proposed a practical strategy for large-scale control of domestic refrigerators for demand peak reduction in distribution systems. The results confirmed that the strategy could contribute not only to reduce peak demand, but also to improve losses and voltage profile of the power distribution systems. In the same year, Kremers et al. [9] presented a multi-agent simulation model to analyze the possibilities of improving grid stability on island systems by local demand response mechanisms. The authors found synchronization effects among the individual refrigerators loads, having undesirable impacts on the system such as oscillations of loads and frequency. Sossan et al. [10] showed the application of a stochastic gray box model to identify electrical power consumption-to-temperature models of a domestic freezer. The authors applied a model predictive control (MPC) to shift the electricity consumption of the freezer, showing the ability of the MPC to exploit the freezer as a demand side resource.

As regards supermarkets and commercial refrigeration systems, in 2012 Hovgaard et al. [11] proposed a MPC scheme for a supermarket that reduced operating costs by utilizing the thermal storage capabilities of refrigerated goods. The authors declared a cost reduction of 9% for a flat-rate fee scenario, and of 32% for a scenario with variable taxes. In another work [12], the same authors considered the MPC of a commercial multi-zone refrigeration system used to cool multiple areas/rooms. Through a sequential convex optimization method, the simulations showed cost savings of 30% compared to a standard thermostat-based control system. Shafiei et al. [13] showed a MPC at supervisory level for refrigeration systems including distributed local controllers. The results showed economic savings of 19% with a proportional-integrative control combined with a specific algorithm, 28% using an energy-efficient scenario, and 36% using an economic MPC scheme. Pedersen et al. [14] investigated control strategies for the aggregation of a portfolio of supermarkets towards the electricity balancing market. The large-scale simulation showed that the portfolio could be used for upward regulation of 900 kW for a two-hour period.

In this work, instead, the application of DSM strategies to a water loop heat pump (WLHP) system was analyzed. The WLHP system was introduced some years ago to benefit from both distributed heating/cooling generation with local control and lower condensing temperature for the refrigeration. The setup consists of an hydraulic loop that can act simultaneously as sink/source for several reversible water/water heat pumps. The most effective operation occurs when the two operating modes are balanced, i.e. in the mid seasons or when some zones require heating or cooling throughout all the year [15, 16, 17].

Thanks to its significant thermal capacity, a WLHP system could be used as a thermal energy storage (TES) with the aim to change the timing of end-use consumption from high-cost periods to low-cost periods, and to increase consumption during off-peak periods. For this reason, the present work aims to analyze the effects on the electricity demand and costs of a DSM strategy implemented in a supermarket, where a WLHP system is integrated with the refrigeration and the HVAC (Heating, Ventilation and Air Conditioning) systems. In this novel setup, for the first time the energy flexibility provided by a water loop reservoir is analyzed. Furthermore, the energy flexibility provided by the supermarket building with its HVAC system is also taken into account and the thermal comfort level of the supermarket was investigated as well. The DSM strategy consists of a DR program activated by real-time pricing (RTP). Given that such strategy is intended also for existing systems, rule based controls are considered. Specifically, the present work takes advantage of predictive rule based controls [18], as their formulation is based on the prediction of the electricity price. Respect to other control systems such as MPCs, predictive rule based controls can be implemented inexpensively and they do not require substantial modifications of the setup under study. Additionally, their formulation is almost independent of the energy system where they are applied, thus they can be easily extended to different energy systems.

2. Methods and case study

The analysis aims at illustrating the DSM potential of a WLHP system which provides heating and cooling in a supermarket building and which is coupled with its refrigeration system for food conservation. A predictive rule based control depending on RTP is implemented to exploit the energy flexibility provided by: i) the building thermal mass by varying the indoor air temperature set-points; ii) the water loop energy storage by adjusting the temperature set-points which regulate its operating conditions; iii) both the building and the WLHP. Furthermore, the influence of the water storage volume of the plant is taken into account. A real supermarket is considered and the DR strategies above described are there implemented. The evaluations are performed by means of a dynamic simulation tool in order to assess the final electricity energy use and cost variations achievable in the DR context.

2.1. Plant configuration

The supermarket is located at the ground floor of a large modern shopping mall. Its heating/cooling production plant configuration is depicted in Figure 1. It can be conceptually divided into two sections: a water loop heat pump (WLHP) system and a commercial refrigeration unit (CRU). The WLHP includes several heat pumps (the hydrofluoroolefin R1234ze(E) was adopted as low-GWP refrigerant) that provide climate control on the supermarket thermal zones. The CRU, instead, consists of a CO_2 transcritical booster system, comprising an additional high-pressure heat exchanger (HX) for heat recovery purposes in favor of the WLHP.

In the heating operating mode, the water loop represents a heat source for the water-to-water/air heat pumps. If the heat transferred from the CO_2 desuperheating process to the water loop is not sufficient, an auxiliary heater based on an air-to-water heat pump intervenes to maintain the water loop temperature at a minimum set-point value. In the cooling season, the heat pumps operate for air conditioning and a dry cooler on the water loop allows heat to be rejected to the external, in order to keep the water temperature as low as possible.

The mass flow rate in the loop is constant and equal to around $150\,\mathrm{t\,h^{-1}}$. A water tank of $50\,\mathrm{m^3}$ is also provided as thermal energy storage, with the aim of reducing the intervention of the auxiliary heater or the dry cooler.

2.2. Supermarket building and heating, cooling and DHW demands

The supermarket is divided into 4 different thermal zones, for a total of 12 areas: the food store (FDS), 7 common areas/hallways (CMA), 2 warehouses

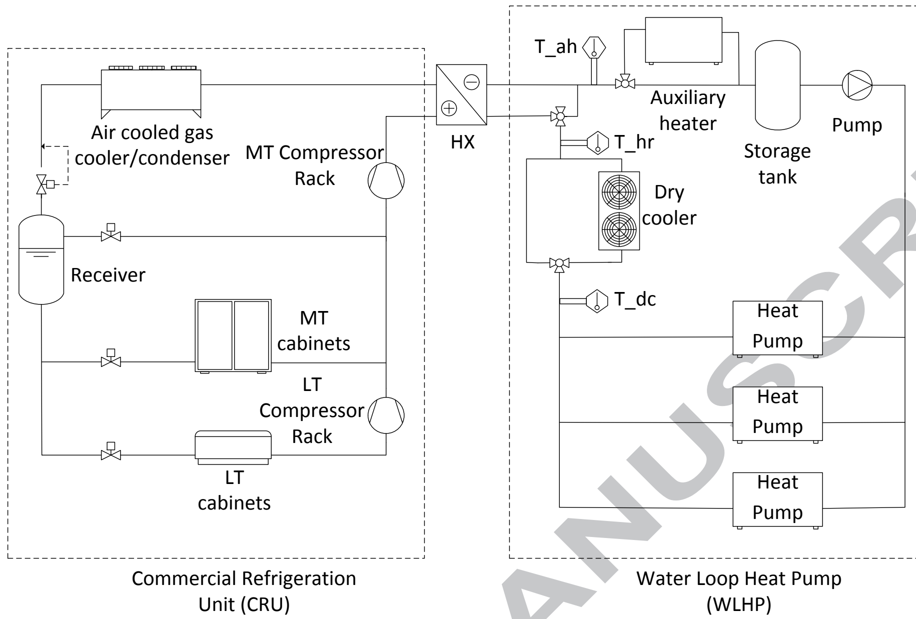

Figure 1: Supermarket heating/cooling production plant configuration.

(WRH) and 2 service areas (SVC). The food store consists of a 6352 m^2 vending area, while the remaining zones occupy an additional surface of 5411 m^2.

The supermarket is sited in Milan, Italy, a location with mild climate conditions. The monthly heating and cooling demands are detailed in Figure 2. The domestic hot water demand, instead, was estimated at a maximum value of 0.250 $m^3\,h^{-1}$ during the opening hours. Further details on the supermarket under study can be found in Polzot et al. [19].

2.3. Refrigeration demand

The refrigeration unit is divided into a medium (MT) and a low temperature (LT) section. The MT section is composed of refrigerated display cabinets for a total length of 208 m and 10 cold rooms, and has a capacity of 140 kW at an evaporating temperature of $-8\,°C$. The LT section, instead, includes frozen food display cases for a total length of 86 m and 2 cold rooms, and has a power of 28 kW at an evaporating temperature of $-35\,°C$.

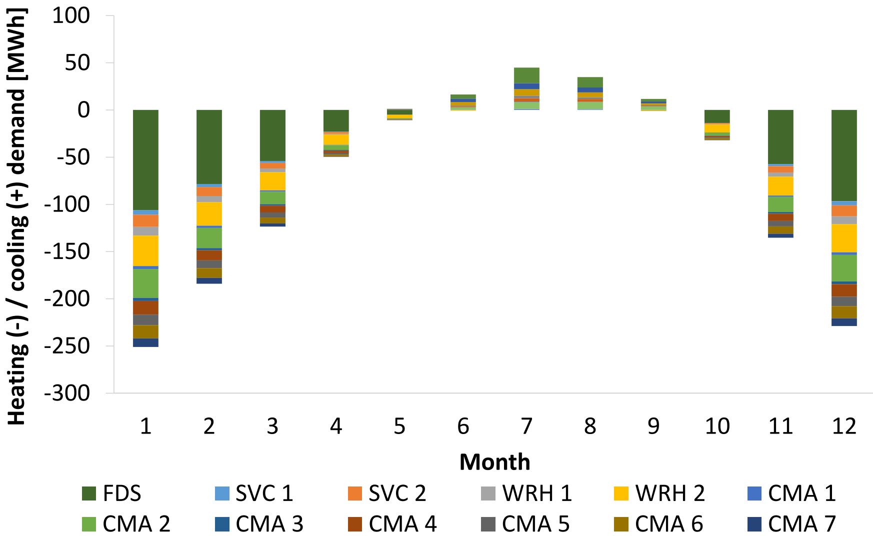

Figure 2: Heating (negative value) and cooling (positive value) demands of the supermarket thermal zones.

The monthly cooling load profile is depicted in Figure 3. Its evaluation is based on a detailed simulation of the refrigerated display cabinets/cold rooms and their interaction with the indoor ambient [20, 21].

3. System modeling

The commercial refrigeration unit, the HVAC system and the supermarket building were modeled in TRNSYS [22], adopting a time step of five minutes. The analysis was carried out for a full year (2017). The following sections describe the components of each system in detail.

3.1. Commercial refrigeration unit

For the CO_2 transcritical booster system with auxiliary compression, the global efficiencies of the compressors were defined as functions of the pressure ratio with BITZER Software [23]. The refrigerant thermodynamic properties, instead, were calculated through CoolProp libraries [24]. The values of the main

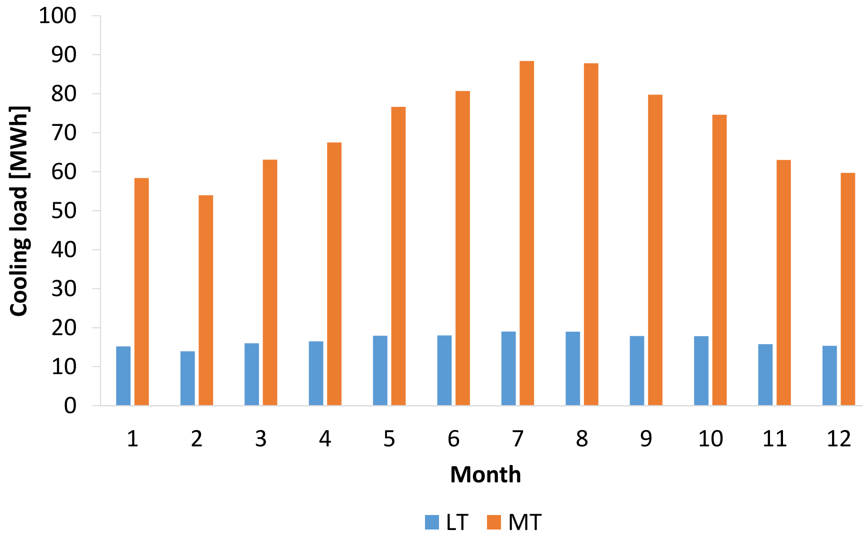

Figure 3: Cooling load of the LT and MT evaporators.

design parameters considered for the commercial refrigeration unit are provided in Table 1.

It should be noted that the CO_2 refrigeration system operational mode (sub-critical, transition or trans-critical) is a function of the ambient temperature, and its discharge and intermediate pressure at the liquid receiver are optimized to maximize the *COP* [19, 20].

3.2. HVAC system

The HVAC system of the supermarket comprises several heat pumps whose vapor compression cycles were implemented in TRNSYS linked to CoolProp libraries. The global efficiencies of the compressors were calculated as function of the pressure ratio by using Frascold Software [25]. The values of the main design parameters considered for the heat pumps are provided in Table 1. Heat pumps correlations for *COP* and *EER* were determined through a mathematical model simulating the R1234ze(E)-based thermodynamic cycle [19] at different operating conditions on the water loop (source side), while the temperature on the load side was kept constant at 45 °C in heating and at 7 °C in cooling.

Table 1: Main design parameters of the commercial refrigeration unit (CRU) and the heat pumps.

Quantity	Value
CRU	
MT evaporating temperature [°C]	-8
LT evaporating temperature [°C]	-35
Superheating at evaporators [K]	5
Approach temperature of the condenser/gas cooler [K]	3
Minimum condensing temperature [K]	8
Liquid receiver pressure (subcritical operation) [MPa]	3.8
Approach temperature of heat recovery [K]	5
Heat pumps	
Useful superheating [K]	4
Subcooling in heating mode [K]	3
Subcooling in cooling mode [K]	2
Approach temperature of the source/load HX [K]	5
Minimum condensing temperature (cooling mode) [°C]	25

3.3. Supermarket building

The model for the supermarket building derives from the outcomes of the EU CommONEnergy project [26]. The building was simulated using the TRNSYS multi-zone building Type 56. The climate conditions of the site were imported in the model of the building by means of Meteonorm weather files [27].

4. Demand side management analysis

The DSM strategy applied to the supermarket under study has the purpose to minimize the yearly electrical energy cost by shifting the electricity demand from peak hours to off-peak hours, using the energy flexibility provided by the WLHP circuit and by the building. It is assumed that the supermarket adheres to a demand response (DR) program based on real-time pricing (RTP) [28].

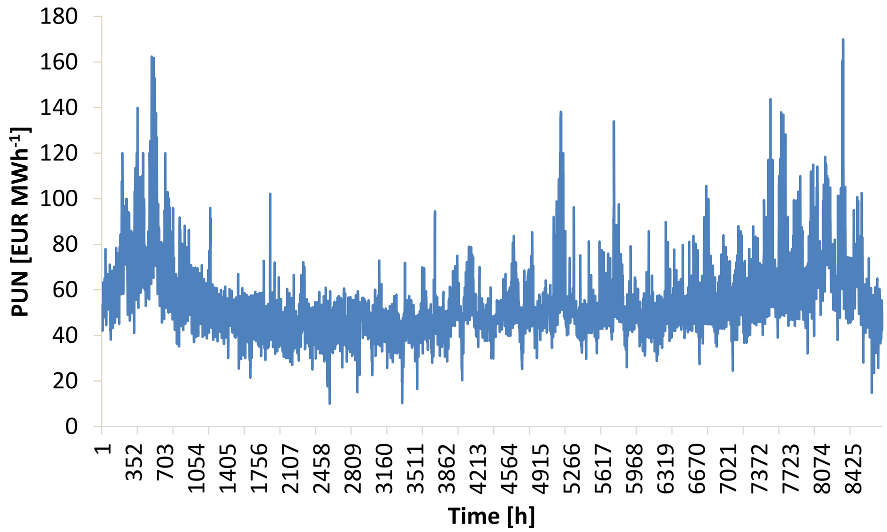

Figure 4: Trend of the Italian PUN in 2017.

Since the proposed supermarket is located in Italy, the Italian PUN (Prezzo Unico Nazionale, National Single Price) was considered as real-time price applied to the customer. The PUN is the electrical energy reference price observed on the Italian Power Exchange: it has a resolution of one hour, represents the price for electrical energy generation only (without taxes) and is based on a day-ahead market [29]. If the electricity price is well-defined 24 hours early, then there exists the possibility to implement a RTP predictive rule based control that tracks the PUN of 2017 (Figure 4).

As already mentioned, two different sections of the supermarket show the possibility to adopt a DR strategy: the heating/cooling of the thermal zones and the WLHP. In the former, the electrical load can be shifted by varying the set-points of the indoor air temperature. This strategy takes advantage of the thermal inertia of the building, but it is also influenced by the thermal capacity of the water loop. In the latter case, instead, the WLHP operation can be varied through the set-point temperatures of its main components (in particular, the auxiliary heater). In this case, the useful thermal inertia is the water circulating in the hydraulic loop.

Following the Italian PUN 2017, both the strategies consist of predictive rule based controls with daily parameters (daily minimum, maximum, and average PUN value) and a hourly resolution. Their specific implementation in the supermarket heating/cooling and in the WLHP system are described in the following sections. An initial configuration referred to as plant baseline is also defined in order to provide a direct comparison between this "DSM off" case and the "DSM on" cases.

4.1. Plant baseline

In its standard configuration without DR programs, the supermarket thermal zones are subdivided into two groups. The first group includes the food store (FDS) and the common areas/hallways (CMA), and is characterized by a heating set-point temperature of 20 °C and a cooling set-point temperature of 26 °C. The second group includes the supermarket warehouse (WRH) and the service areas (SVC), and has a heating set-point temperature of 18 °C and a cooling set-point temperature of 30 °C. We will refer to this specific supermarket heating/cooling configuration as Build 0.

As concerns the WLHP, the heat recovery from the refrigeration unit and the auxiliary devices of the water loop are activated according to the following control strategy, which will be referred to as WLHP 0:

- in wintertime, when the water loop temperature drops below a heat recovery set-point temperature, $T_{\mathrm{hr}} = 20\,°\mathrm{C}$, the heat recovery from the refrigeration unit is activated;
- in wintertime, when the water loop temperature drops below a second heating set-point temperature, $T_{\mathrm{ah}} = 10\,°\mathrm{C}$, the auxiliary heater is activated;
- in summertime, when the water loop temperature rises to a cooling set-point temperature, $T_{\mathrm{dc}} = 20\,°\mathrm{C}$, the dry-cooler is activated to cool the water loop.

Table 2: Yearly electricity consumption and cost of the baseline configuration (Build 0 + WLHP 0 + $V_{\text{tank}} = 50\,\text{m}^3$).

Quantity	Symbol	Value
Heat pumps [MWh]	E_{hp}	223.28
Dry cooler [MWh]	E_{dc}	10.58
Refrigeration unit [MWh]	E_{refr}	289.94
Auxiliary heater [MWh]	E_{ah}	217.57
Circulating pump [MWh]	E_{pump}	8.83
Total energy [MWh]	E_{tot}	750.20
Total cost [kEUR]	C_{tot}	45.63

Another important component of the WLHP circuit is the water tank. In fact, its volume directly influences the water loop thermal capacity and, as it will be seen in the following sections, represents a relevant parameter of the DSM analysis. In summary, the plant baseline is the system combining the configurations Build 0 and WLHP 0 with a water tank volume, V_{tank}, of $50\,\text{m}^3$. Table 2 reports the yearly electricity consumption and cost of the baseline configuration, subdivided among the main energy systems of the supermarket.

4.2. DR using energy flexibility from space heating and cooling

The set-points of the supermarket indoor air temperature can be modified in order to shift the electrical load of the heat pumps. In the present analysis, two cases were considered. In the first one (Build 1), the baseline set-points were allowed to vary by a maximum of $\pm 1\,°\text{C}$, while in the second one (Build 2) the variation is equal to a maximum of $\pm 2\,°\text{C}$. Higher variations were not considered, in order to maintain the zones thermal comfort, as it will be discussed in the results.

The predictive rule based control that regulates the indoor ambient temperature is governed by the following hourly set-point equation, function of the

PUN:

$$T_{\mathrm{sp,DSM},i} = \begin{cases} T_{\mathrm{sp},i} + \Delta T_{\mathrm{sp}} \left(\frac{PUN_i - \overline{PUN}_i}{PUN_{\max,i} - \overline{PUN}_i} \right) & \text{if } PUN_i \geq \overline{PUN}_i \\ T_{\mathrm{sp},i} + \Delta T_{\mathrm{sp}} \left(\frac{PUN_i - \overline{PUN}_i}{\overline{PUN}_i - PUN_{\min,i}} \right) & \text{if } PUN_i < \overline{PUN}_i \end{cases} \tag{1}$$

where:

- i is the i-th hour of the year;
- $T_{\mathrm{sp},i}$ is the hourly baseline heating/cooling set-point temperature, as defined in Section 4.1;
- ΔT_{sp} is equal to ± 1 or $\pm 2\,°\mathrm{C}$ according to the chosen case (Build 1 or 2) and the HVAC mode (+ for cooling, − for heating);
- PUN_i is the hourly value of the PUN;
- $\overline{PUN}_i$ is the average daily value of the PUN corresponding to i-th hour;
- $PUN_{\max,i}$ is the maximum daily value of the PUN corresponding to i-th hour;
- $PUN_{\min,i}$ is the minimum daily value of the PUN corresponding to i-th hour.

In order to simulate a realistic and simple control system, the set-point $T_{\mathrm{sp,DSM},i}$ does not assume continuous values but has a resolution of 1 °C. The predictive rule based control defined in Equation (1) has been designed to allow the heat pumps to absorb less energy when the hourly PUN is higher than the corresponding average daily PUN, and to consume more energy when the hourly PUN is lower than the corresponding average daily PUN. For example, Figure 5 shows how the food store heating set-point varies between Build 0, 1 and 2.

4.3. DR using energy flexibility from WLHP

The WLHP operation is regulated by the set-point temperatures of the heat recovery exchanger, the auxiliary heater and the dry cooler. The heat recovery

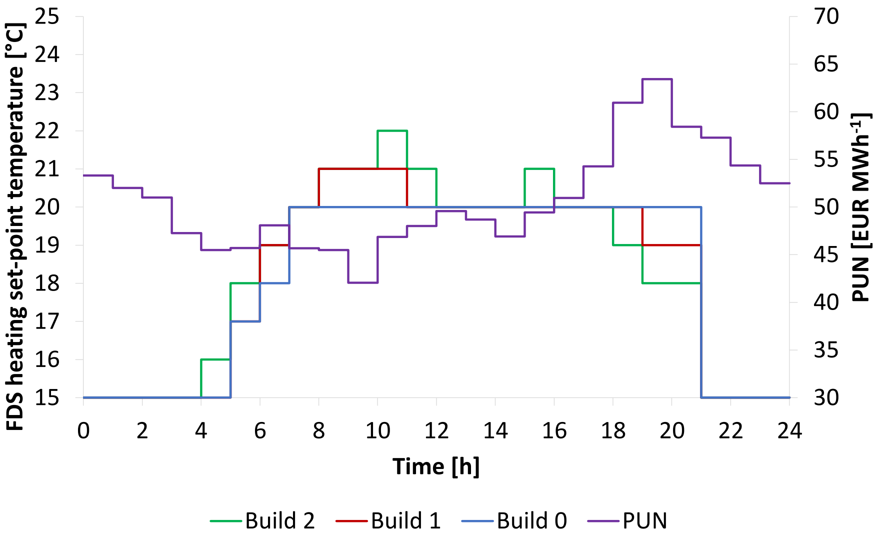

Figure 5: Heating set-point temperature of the food store (FDS) in Build 0, 1 and 2 during a typical day.

operation is optimized for the operational mode of the CO_2 refrigeration system (sub-critical, transition, trans-critical), thus this set-point was not modified according to a DR strategy. As regards the dry cooler, Table 2 shows that its electricity consumption is much lower than that of the auxiliary heater, thus a DR strategy applied to this component would not be so beneficial as it could be for the auxiliary heater.

The DR strategy in the WLHP was therefore limited to the auxiliary heater. In the same fashion of the space heating and cooling, a predictive rule based control described by Equation (1) was implemented in the simulation environment. As the auxiliary heater is an heating device, ΔT_{sp} assumed a negative value and was allowed to vary of -1, -2 and -3 °C. These three configurations will be referred to as WLHP 1, 2 and 3, respectively.

4.4. Economic analysis

As highlighted in Section 4.1, the volume of the water tank represents a relevant parameter of the analysis. Thus, it is important to quantify properly the tank installation cost as a function of its storage volume. In literature, it is reported that thermal energy storage devices with hot water as storage medium have investment costs of 0.1-10 EUR kWh^{-1} [30]. TES systems for sensible heat are rather cheap because they consist basically of a simple tank for the storage of water and the equipment to charge/discharge [31]. For the water tank of the present study, we considered a specific cost of 50 EUR m^{-3}, price that is justified by the reduced amount and quality of thermal insulation required (the water loop typically works in the range 10-30 °C). Since there are no strong scale effects for water-based TES systems used in large installations [32], the chosen specific cost was applied to all the volumes considered in this study. Taking into account a depreciation period of 20 years, the annual specific cost of the water tank would be 2.5 EUR $m^{-3}\,y^{-1}$.

It is also worth noting that the electricity cost associated to the baseline configuration (Table 2) derives from a real-time pricing tariff based on the PUN. Actually, typical non-household consumers such as the one under study usually adopt time of use (e.g., high-low tariff schemes) or fixed price tariffs. Referring to the data provided by Eurostat for non-household consumers, in 2017 the average electricity price in Italy (excluding taxes and levies) was equal to 82.10 EUR MWh^{-1} [33]. Taking into account a fixed tariff based on this price, subtracted by a conservative -10% amount that accounts for the supplier's markup, the electricity price would be 73.89 EUR MWh^{-1}. With this price, the total electricity cost of the plant baseline would be 55.43 kEUR, cost that is around 10 kEUR higher than that associated to the PUN-based real-time pricing tariff.

5. Results of the analysis

The DR strategies defined in the previous section determine different variations in the annual electricity consumption and cost. In the following sections, we will analyze the impact of each strategy (in the space heating/cooling or in the WLHP), then we will see how the two strategies can be combined to provide

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Table 3: Yearly electricity demand and cost variation of the main energy systems of the supermarket for different indoor temperature rule based controls (WLHP 0 and $V_{\text{tank}} = 50\,\text{m}^3$).

Quantity	Build 0	Build 1	Build 2
E_{hp} [MWh]	223.28	224.58	231.28
E_{dc} [MWh]	10.58	11.12	11.64
E_{refr} [MWh]	289.94	290.30	290.71
E_{ah} [MWh]	217.57	219.40	227.62
E_{pump} [MWh]	8.83	8.74	8.61
E_{tot} [MWh]	750.20	754.14	769.86
C_{tot} [kEUR]	45.63	44.35	43.77

an adequate operation of the supermarket energy plant.

5.1. Results of the space heating and cooling DR strategy

For the supermarket under study, the rule defined in Equation (1) determines an increase of the yearly electricity demand, both in Build 1 and 2. In Table 3 it is possible to see what happens respect to the baseline Build 0, as defined in Section 4.1 ($V_{\text{tank}} = 50\,\text{m}^3$). Going from the baseline to Build 1, the yearly energy demand increases of 0.53%, while the increase is of 2.62% from the baseline to Build 2. The highest energy demand increase belongs to the auxiliary heater: from the baseline to Build 2, it is equal to 4.62%. This is a direct consequence of the increased demand of the heat pumps, which require hotter water in the winter season to satisfy the modified heating set-points.

Figure 6 shows how the daily electrical absorption of the heat pumps varies according to the different DR strategies defined by Equation (1). Respect to Build 1, Build 2 amplifies the effect of the predictive rule based control by following the PUN more closely.

It is interesting to analyze how the electricity demand varies when a larger flexibility is provided to the supermarket heating/cooling production by increas-

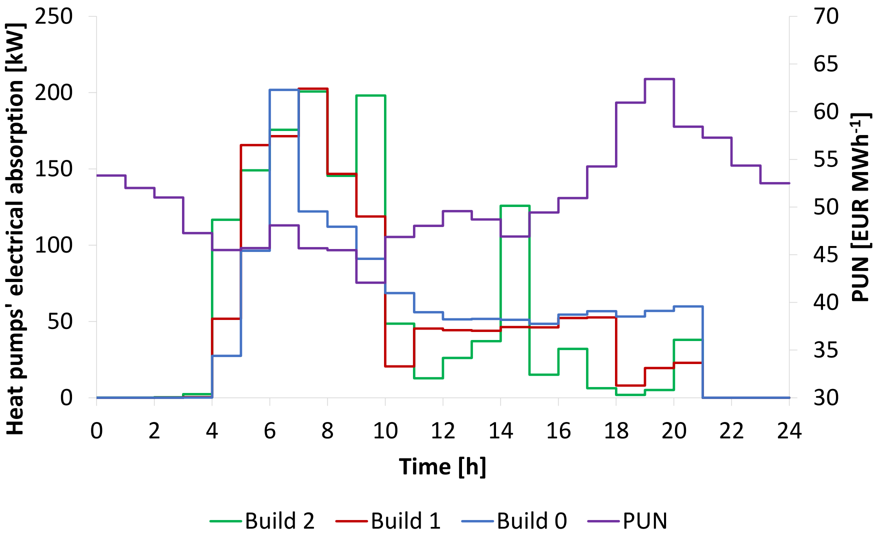

Figure 6: Electrical power absorbed by the heat pumps in a typical day (WLHP 0 and $V_{\mathrm{tank}} = 50\,\mathrm{m}^3$).

ing the water loop volume through a larger water tank. As depicted in Figure 7, the minimum overall energy demand lies approximately between 100 and 150 m^3 for the different cases, while the consumption tends to increase for larger volumes. The increase is entirely due to the auxiliary heater, which has to heat a larger quantity of water.

Figure 7 also reports the trend of the yearly electricity cost for different DR strategies and water volumes. Focusing on the 50 m^3 case, it is possible to note that there is a cost saving in adopting a DR strategy. Going from the baseline to Build 1, the relative cost saving is equal to 2.79%, around 1273 EUR. Implementing the Build 2 DR strategy, there is a relative saving of 4.06%, for an amount of 1853 EUR. These savings require no modification of the supermarket plant configuration.

At this point, it is worth evaluating the possibility of an additional cost saving deriving from the use of larger water reservoirs. Although in Figure 7 there seems to be an advantage in adopting tanks larger than 50 m^3, such an

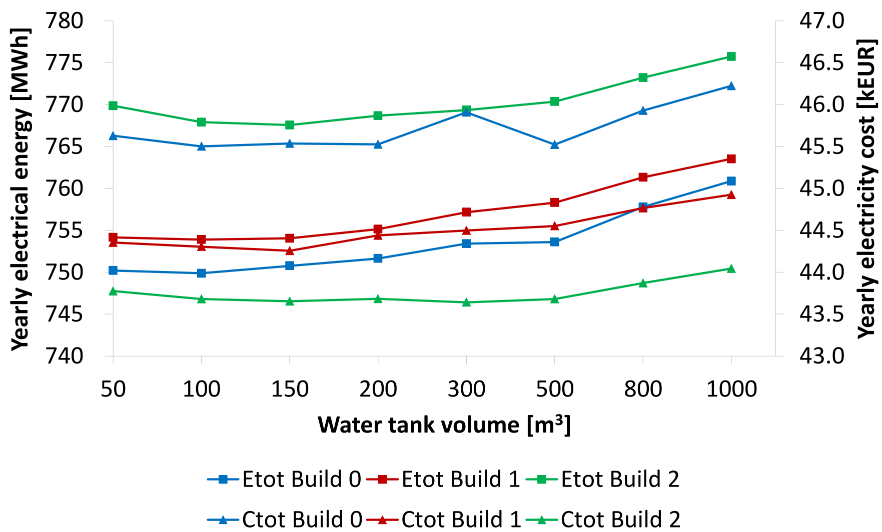

Figure 7: Yearly electricity demand and cost variations for different indoor temperature set-points and water tank volumes (WLHP 0).

investment would not justify the consequent small electricity cost saving. For instance, in Build 2 the substitution of a $50\,\mathrm{m}^3$ water tank with a $300\,\mathrm{m}^3$ one results in an additional annual saving of only 133 EUR, amount that is not able to compensate for the annual depreciation cost of a new water tank.

In conclusion, the DR strategy applied to the heat pumps seems to provide a tangible energy cost saving. However, the modification of the space heating/cooling set-points clearly influences the thermal comfort quality of the supermarket thermal zones, therefore this aspect needs to be investigated carefully. To this purpose, Figure 8 depicts how the predicted mean value, PMV, varies in the food store for Build 0, 1 and 2. In general, all the configurations guarantee an acceptable degree of thermal comfort, which clearly worsens when the temperature set-point variation is larger. Considering a working schedule of 4380 hours in a year (12 hours every day), Build 0 is in the discomfort condition $|PMV| > 0.5$ for 40 hours of the cooling period, which correspond to a 0.91% of the total. Build 1 is in the discomfort condition for 78 hours (1.78%), while Build 2 shows a discomfort level of 124 hours (2.83%). In any case, the yearly

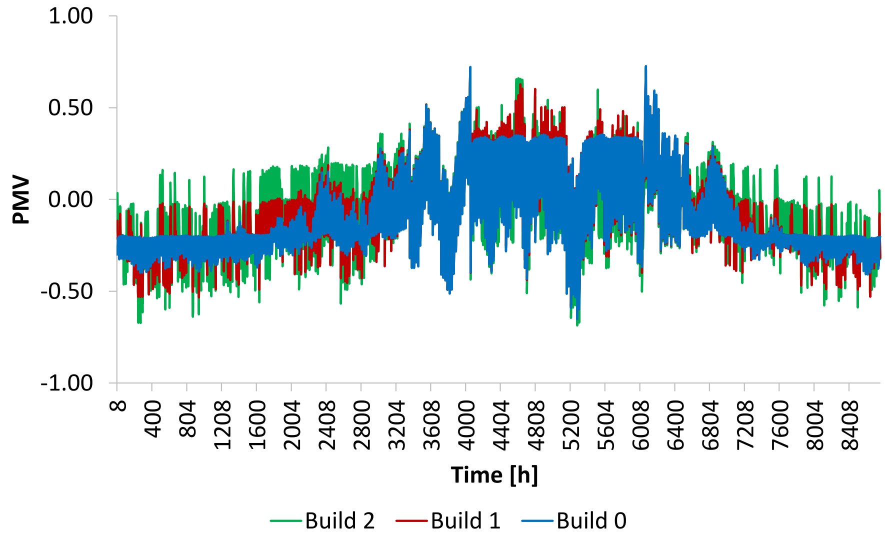

Figure 8: Yearly predicted mean value (PMV) of the food store (WLHP 0 and $V_{\mathrm{tank}} = 50\,\mathrm{m}^3$).

percentage discomfort level is well below 10%, value that is typically considered the maximum allowed discomfort level in a commercial activity.

5.2. Results of the WLHP DR strategy

The annual electricity consumption and cost for the DR strategies implemented in the auxiliary heater are provided in Table 4, that refers to the Build 0 case with a $50\,\mathrm{m}^3$ water tank volume. Under the energy point of view, it is possible to see that the adoption of any DR strategy (i.e., WLHP 1, 2 or 3) determines a slightly higher consumption (+0.30% for the WLHP 3 case), which is basically due to the auxiliary heater.

The hourly effect of the WLHP DR strategies is depicted in Figure 9, which shows the daily trend of the auxiliary heater electrical absorption for the different WLHP set-point variations. A wider set-point is able to follow the PUN trend with greater accuracy.

Figure 10 shows how the electricity consumption and cost vary with the adoption of water tanks of variable size. Energy and cost have opposite trends, and it can be noted that there exists the possibility to obtain a considerable

Table 4: Yearly electricity demand and cost variation of the main energy systems of the supermarket for different auxiliary heater rule based controls (Build 0 and $V_{\text{tank}} = 50\,\text{m}^3$).

Quantity	WLHP 0	WLHP 1	WLHP 2	WLHP 3
E_{hp} [MWh]	223.28	223.33	223.06	222.52
E_{dc} [MWh]	10.58	10.60	10.59	10.61
E_{refr} [MWh]	289.94	289.94	289.94	289.94
E_{ah} [MWh]	217.57	217.72	218.47	220.58
E_{pump} [MWh]	8.83	8.82	8.82	8.81
E_{tot} [MWh]	750.20	750.41	750.88	752.46
C_{tot} [kEUR]	45.63	45.50	45.39	45.30

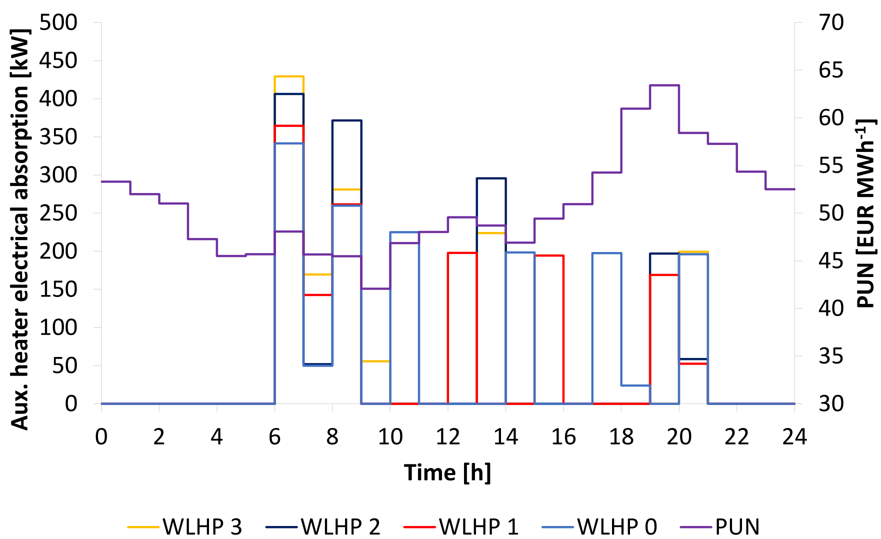

Figure 9: Electrical power absorbed by the auxiliary heater in a typical day (Build 0 and $V_{\text{tank}} = 50\,\text{m}^3$).

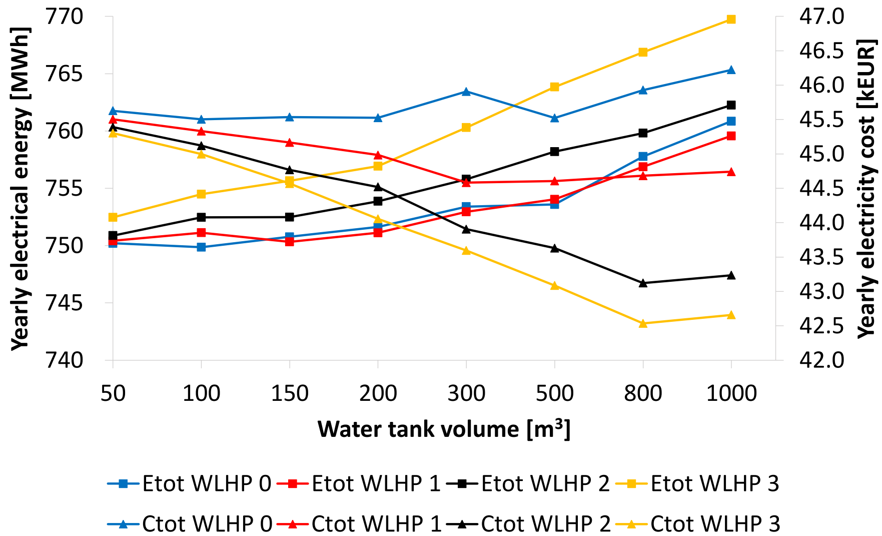

Figure 10: Yearly electricity demand and cost variations for different auxiliary heater set-points and water tank volumes (Build 0).

cost saving when a wide DR strategy is combined with a large water tank. In particular, the WLHP 3 rule seems to guarantee a promising result in terms of cost saving respect to the baseline (WLHP 0), showing a beneficial effect up to a volume of 800 m^3, effect that is then neglected for larger tanks due to excessive thermal losses. Respect to the baseline case, the WLHP 3 case with a 800 m^3 reservoir guarantees a cost saving of about 3092 EUR (-6.78%).

In conclusion, the WLHP DR strategy applied to the auxiliary heater shows a quantifiable cost saving, that is particularly sensible to the size of the water tank adopted. In this case, it is important to take into account the installation cost of the thermal energy storage. This aspect will be discussed in the following section.

5.3. *Results of combined space heating/cooling and WLHP DR strategies*

The DR strategy defined for the space heating/cooling and the auxiliary heater can be combined to verify if additional cost savings are feasible. Referring again to the most favorable WLHP 3 case, Figure 11 depicts the electricity

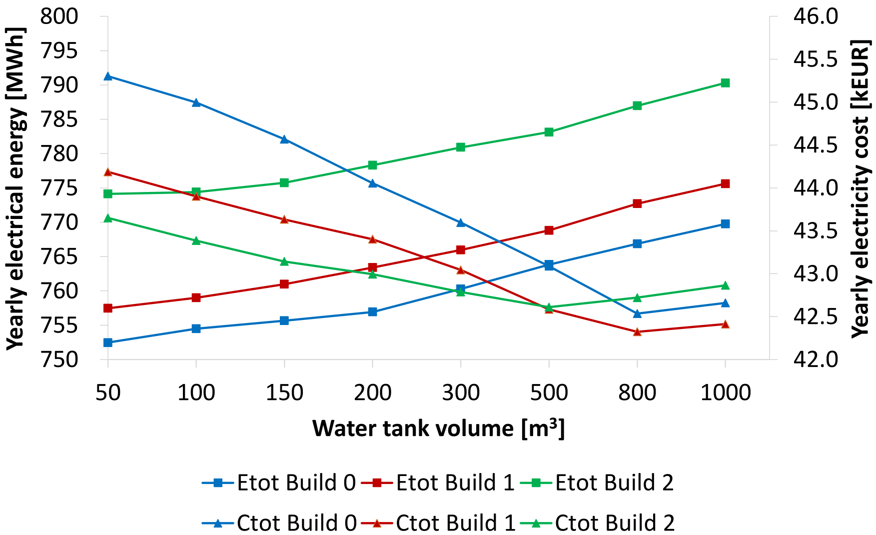

Figure 11: Yearly electricity consumption and cost vs. different water tank volumes (Build 0/1/2 + WLHP 3).

energy and cost trends when the WLHP 3 DR strategy is combined with the supermarket heating/cooling DR strategies (i.e., Build 1 and 2). While the energy trend increases with the water tank volume, the cost trend presents a minimum value. Specifically, Build 1 combined with the WLHP 3 rule guarantees a minimum yearly cost with a water volume of 800 m^3, value that is 212 EUR lower than the corresponding Build 0 case and more than 2000 EUR lower than the corresponding Build 1 + WLHP 0 case. As regards Build 2, the WLHP 3 configuration shows a minimum electricity cost for a water volume of 500 m^3; respect to the Build 0 case with the same water volume, the cost saving is of 476 EUR, while respect to Build 2 + WLHP 0 the saving is equal to 1163 EUR.

In terms of total annual electricity cost, it is clear from Figure 11 that the best configuration is Build 1 + WLHP 3 with a water tank volume of 800 m^3. Provided that its installation is not problematic in the plant under study, a water tank of this size has a considerable depreciation cost (2000 EUR y^{-1}) that does not justify its adoption. Combining the yearly electricity cost of the considered configurations with the depreciation cost of water tanks larger than $50\,\mathrm{m}^3$, the analysis revealed that the only setup able to provide an additional economic convenience respect to the best $50\,\mathrm{m}^3$ configuration (i.e., Build 2 + WLHP 3) is the same Build 2 + WLHP 3 configuration with a $200\,\mathrm{m}^3$ water tank. In this case, in fact, it would be possible to save other 156 EUR respect to the $50\,\mathrm{m}^3$ case, clearly considering the depreciation of the tank that is equal to 500 $\mathrm{EUR\,y^{-1}}$.

In summary, the maximum electricity cost saving of the supermarket is achieved for the configuration Build 2 + WLHP 3 with a water storage tank of $200\,\mathrm{m}^3$. Respect to the baseline, the selected configuration offers an electricity cost saving of 2133 EUR (4.67%), amount that includes the 20-year depreciation cost of the water tank. Another interesting configuration is Build 2 + WLHP 0 (discussed in Section 5.1), which requires no water storage tank larger than $50\,\mathrm{m}^3$ and ensures a cost saving respect to the baseline of 1853 EUR (4.06%). Configurations with only DR strategies applied to the auxiliary heater (Section 5.2) are of no economic interest as they always require larger storage tanks to be really effective, thus removing any cost saving in the short period. Finally, supposing that the supermarket baseline does not adhere to a PUN-based RTP electricity tariff but adopts a standard fixed tariff, the DR configuration Build 2 + WLHP 3 with a water tank of $200\,\mathrm{m}^3$ would provide an annual cost saving of 11 938 EUR (−21.54%), while the DR configuration Build 2 + WLHP 0 would guarantee an annual cost saving of 11 658 EUR (−21.03%). These cost savings should represent a more realistic quantification of the amounts that could be saved with an existing plant. Indeed in this paper a specific case study was analyzed and thus the economic savings are strictly related to it. However, the general conclusions about the effect of DR strategies applied to a WLHP system can be easily extended to similar systems.

6. Conclusions

The DR analysis of the supermarket integrated HVAC, refrigeration and WLHP system showed that two configurations are the most economically effective. The first configuration consists of a DR strategy applied to the space heating/cooling, which allows to vary the internal air temperature set-points up to 2 °C. Respect to the baseline, this setup ensures an annual cost saving of 1853 EUR, does not worsen significantly the thermal comfort quality of the thermal zones, and is basically inexpensive as it does not require a larger water reservoir. The second configuration combines the predictive rule based controls applied to the space heating/cooling and the WLHP auxiliary heater, device installed in the water loop to integrate the heat from the CO_2 de-superheating process. The flexibility of the auxiliary heater (±3 °C) is given by the thermal inertia of the water circulating in the hydraulic loop. In this case, the best economic saving (2133 EUR y^{-1}) can be obtained with the installation of a 200 m^3 water tank. Both the configurations guarantee an yearly electricity cost saving of more than 4% respect to the baseline.

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Highlights

1. Supermarkets are ideal candidate for demand side management (DSM) strategies
2. A supermarket integrated HVAC, refrigeration and water loop HP (WLHP) was analyzed
3. Demand response (DR) based on real-time pricing rule based controls was used
4. DR strategies were applied to the supermarket heating/cooling and the WLHP
5. Two setups guarantee the highest annual electricity cost savings (4.06% and 4.67%)